N91-28114

PROGRESS IN PROTON TRANSPORT CODE DEVELOPMENT: MICROELECTRONIC APPLICATION

551-72
26632
P11

Duc M. Ngo, W.W. Buck, and T.N. Fogarty
Physics Department
Hampton University
Hampton, VA

and

J.W. Wilson
NASA, Langley Research Center
Hampton, VA

ABSTRACT

The process of target nucleus fragmentation by energetic protons is examined and their effects on microelectronic devices considered. A formalism for target fragment transport is presented with future applications to microelectronic effects discussed.

PROGRESS IN PROTON TRANSPORT CODE DEVELOPMENT: MICROELECTRONIC APPLICATION

Introduction

Since the early suggestion that some spacecraft anomalies may result from the passage of the galactic ions through microelectric circuits (ref. 1), it has now been well established as a fact. Although the direct ionization of protons appear as unlikely candidates, their nuclear reaction products are suspected as a source of Single Event Upset (SEU) phenomena (ref. 2-4). As a result a number of fundamental experimental and theoretical studies were undertaken to better understand the phenomena. McNulty and coworkers examined the energy deposition of proton reaction products in Si using surface barrier detectors of various thickness from 2.5 to 200 μm (ref. 5). They also developed a Monte Carlo code for theoretical evaluation of energy deposition from such products (ref. 5,6). Comparisons of McNulty's work with the well established MECC7 developed by Bertini and coworkers at Oak Ridge National Laboratory showed some differences in predicted reaction products and even greater differences in energy spectral contributions (ref. 7). An evaluation of Si reaction products was likewise made by Petersen (ref. 4), and although no direct comparison was made to McNulty's experiments, an estimate of SEU rates in the trapped proton environment was made.

Following these fundamental studies came more detailed application to devise specific questions. Bradford evolved an energy deposition formalism (ref. 8) using the cross sections of Hamm et. al. (ref. 7). The McNulty Group applied the Monte Carlo model to DRAM devices with reasonable success and discussed the implications of heavy ion SEU phenomena on proton induced SEU events through secondary reaction processes (ref. 9). The fundamental consideration is the evaluation of the energy deposited within the sensitive volume (depletion region) of the device in question due to a passing proton. The ionization of the proton itself makes only a small contribution to the critical charge. Nuclear reaction events usually produce several reaction products (usually a heavy fragment and several lighter particles although a few heavy fragments may be produced simultaneously on some occasions) and all of the resultant products can make important contributions to the energy deposited. Such nuclear event products are of course correlated in both time and space.

There are three distinct approaches to a fundamental description of the energy deposition events. McNulty and coworkers have developed a Monte Carlo code in which multiparticle events are calculated explicitly including spatial and specific event (temporal) correlation effects. Although this is the most straightforward way of treating the full detail, it is a complex computational task. A second class of methods begins with the volumetric source of collision events and calculates the SEU probability using the cord length distribution (ref. 8,10). Although in principle the correlation effects could be so incorporated, they appear to be ignored in both of the cited references. A third approach, in which LET distributions and cord length distributions are used, seems most appropriate for external sources (ref. 11,12). It would seem that this last approach applies if the LET distribution from external sources is constant over the sensitive volume but its applicability to volumetric sources is questionable. At the very least this approach ignores correlation effects.

In an earlier work we examined nuclear data bases for biological systems (ref. 13). In that work we found that the MECC7 results underestimated by nearly a factor of two the cross section for multiple charged ion products. In a more detail analysis, we found the Silberberg-Tsao fragmentation parameters to be superior to the MECC7 results (ref. 14). The primary differences appear for the lighter of the multiple charged fragments. Further comparison with experiments of Al targets show all three Monte Carlo nuclear models (OMNI, VEGAS as well as MECC7) to underestimate production cross sections for products lighter than fluorine in proton induced reaction. Although these intranuclear cascade models are capable of representing multiparticle correlation, the inherent inaccuracies in predicting cross sections is a serious limitation. In the present paper we examine the implication of the nuclear recoil effects on electronic devices and begin the development of a formalism for application to specific device parameters.

Microelectronic Upsets

An electronic device is sensitive to the sudden introduction of charge into active elements of its circuits. The amount of such charge which is sufficient to change state in a logic circuit is called the critical charge. There is a rough relationship between the critical charge Q_c and the device feature size L (ref. 11) as shown in Fig. 1. This relationship is approximately

$$Q_c \approx 0.0156L^2 \tag{1}$$

where Q_c has units pC and L has units μm. Upsets in a device are then dependent on the charge produced compared to the critical charge.

The charge released ΔQ in a material due to the passage of an energetic ion is related to the kinetic energy lost ΔE during the passage given by

$$\Delta Q = \frac{\Delta E}{22.5} \tag{2}$$

where ΔQ has units pC and ΔE has units MeV.

The energy lost by an ion in passing through a region is related to its stopping power $(-\frac{dE}{dx} = S_z(E'))$ in the medium. The distance traveled before coming to rest is

$$R_z(E) = \int_0^E \frac{dE'}{S_z(E')}. \tag{3}$$

If an ion is known to come to rest in distance x then its energy is found through the inverse of the relation (3) as

$$E = R_z^{-1}(x) \tag{4}$$

and we note that equation (4) is used to calculate energy loss. The energy loss by an ion of charge Z and energy E in passing through a device with collection length L will have its energy reduced by

$$\Delta E = E - R_z^{-1}\,[R_z(E) - L_c] \tag{5}$$

and

$$L_c = W_{epi} + W_n \tag{6}$$

where W_{epi} is the epi thickness and W_n is the depletion width.

We note in passing that ΔE does not depend on the particle isotope (i.e., ion mass). The range energy relations described elsewhere (ref. 14) are utilized. As a practical matter to reduce numerical error inherent to numerical interpolation, we use

$$\Delta E = R_z^{-1}[R_z(E)] - R_z^{-1}[R_z(E) - L_c] \tag{7}$$

in place of equation (5). Note the result of equation (5) depends on the global error (fixed at 1 percent) of the code while equation (7) depends only on the local relative error (quite small). The charge introduced is given by equation (2) and (7). An example of a particular collection length of 2μm is shown in Fig. 2 for each ion type. We assume a simplified geometry in which the channel length and width and the collection length are take as equal to the feature size. We take the critical energy as the upper and lower limit of the range of energy for which

$$\Delta Q(E) \geq Q_c \tag{8}$$

which depends on the feature size L. The ion mass for each A is taken as the natural mass. The critical energies are shown in Fig. 3. Also shown in Fig. 3 are the average recoil energy from the fragmentation of ^{16}O and ^{28}Si produced by collision with a high energy proton (ref. 14).

It is doubtful that any of the fragments are produced in the 4μm and larger devices (note that we have used simplified geometries). Also, the lighter fragments of Li, He, and H are not suspected for SEU events, at least in this simple geometry. Also note that Fig. 3 is applicable to cosmic ray ions.

Nuclear Fragmentation Cross Section

Although nuclear fragmentation has been under study for nearly 50 years, the absolute cross sections still stir some controversy. The experimental problem is that the reaction products could be directly observed only in recent years and even now only in rather sophisticated experiments. Rudstam studied the systematics of nuclear fragmentation and supposed the fragment isotopes to be distributed in a bell-shaped distribution about the nuclear stability line (ref. 15). Silberberg et al. continued the Rudstam parametric approach and added many correction factors as new experimental evidence became available (ref. 12).

Concurrently, Monte Carlo simulation of the Serber model (ref. 16) coupled with final decay through compound nuclear models showed some success (ref. 7, 17). Even so, Monte Carlo simulations show little success in predicting fragments whose mass is small compared to the original target nuclear mass (ref. 13,18). Of the various models for nucleon induced fragmentation in ^{28}Si, probably that of Silberberg et al. (ref. 12) is currently most reliable. The main limitation of their model is that only inclusive cross sections are predicted and particle correlations will undoubtedly prove important in predicting SEU.

Measurements of ^{27}Al fragmentation in proton beams have been made by Kwaitkowski (ref. 18). These experiments are compared in Fig. 4 to the Monte Carlo results of OMNI, VEGAS, and MECC7.

Also shown are the results of Silberberg et al. Generally the Silberberg et al. results appear to be within a factor of 2 of the experiments and this is the only model which predicts significant contributions in the important range below $Z_f = 6$.

The spectrum of average recoil energy is calculated using the Silberberg - Tsao cross sections and compared with the spectrum according to Bertini cross sections in Fig. 5. The Bertini cross section is a serious underestimate above 8 MeV and greatly overestimates below 3 MeV. Experimental evidence indicates that even the Silberberg-Tsao values are too small above 6 MeV (ref. 18).

Nuclear Recoil Transport

The transport of the recoil fragments is described by the following

$$[\Omega \cdot \nabla - \frac{\partial}{\partial E} S_z(E)]\phi_z(x,\Omega,E) = \zeta_z(\Omega,E) \tag{9}$$

where $\phi_z(x,\Omega,E)$ is the ion flux and $\zeta_z(\Omega,E)$ is the ion source density assumed to be uniformly distributed through the media. The solution to equation (9) is to be found in the closed region bounded by the surface Γ subject to the boundary condition

$$\phi_z(\Gamma,\Omega,E) = F_z(\Omega,E) \quad \text{for } n \cdot \Omega < 1 \tag{10}$$

where n is the outward directed normal. The solution as found using the method of characteristic (ref. 19) is:

$$\phi_z(x,\Omega,E) = \frac{S_z(E_b)}{S_z(E)} \phi_z(\Gamma,\Omega,E_b) + \frac{1}{S_z(E)} \int_E^{E_b} \zeta_z(\Omega,E')dE' \tag{11}$$

where Γ is taken as the point on the boundary by projecting x along $-\Omega$ and

$$E_b = R_z^{-1}[R_z(E) + b] \tag{12}$$

where

$$b = \Omega \cdot (x - \Gamma). \tag{13}$$

Using equation (11), we may evaluate the spectrum of particles leaving the region which can be related to the spectrum of energy deposited in the media. Such a task will be completed in the near future.

References

1. D. Binder, et al., IEEE Nucl. Sci. Trans., 1975, NS-25, 2675-2680.
2. R.C. Wyatt, P.J. McNulty, P. Toumbas, P.L. Rothwell, and R.C. Filz, IEEE Nucl. Sci. Trans., 1979. NS-26, 4905 - 4910.
3. C.S. Guenzer, R.G. Allen, et al., IEEE Nucl. Trans., 1980 NS-27, 1485-1489.
4. E.L. Petersen, IEEE Nucl. Sci. Trans., 1980, NS-27, 1485-1489.
5. P.J. McNulty, G.E. Farrell, R.C. Wyatt, P.L. Rothwell, R.C. Filz, and J.N. Blanford, IEEE Nucl. Sci. Trans., 1980, NS-27, 1516-1520.
6. P.J. McNulty, G.E. Farrell, and W.P. Tucker, IEEE Nucl. Sci. Trans., 1981, NS-28, 4007-4012.
7. R.N. Hamm, M.L. Rustgi, H.A. Wright, and J.E. Turner, IEEE Nucl. Sci. Trans., 1981, NS-28, 4004-4006.
8. J.N. Bradford, IEEE Nucl. Sci. Trans., 1982, Ns-29, 2085-2089.
9. J.M. Bisgrave, J.E. Lynch, P.J. McNulty, W.G. Abdel-Kader, V. Kletnicks, W.A. Kolasinski, IEEE Nucl. Sci. Trans., 1986, NS-33, 1571-1576.
10. K.W. Fernald and S.E. Kerns, IEEE Nucl. Sci. Trans., 1988, Ns-35, 981-986.
11. E.L. Petersen, P. Shapiro, J.H. Adams, and E.A. Burke, IEEE Nucl. Sci. Trans., 1982, 2055-2063.
12. R. Silberberg, C.H. Tsao, and J. Letaw, D. Reidel Publ. Co., 1976, 49-81.
13. J.W. Wilson, S. Y. Chun, W.W. Buck, and L.W. Townsend, Health Physics, 1988, 55, 817-819.
14. J.W. Wilson, L.W. Townsend, S.Y. Chun, S.L. Lamkin, et al., 1988, NASA TP 2887.
15. C. Rudstam, Zeitschrift fur Naturforschung, 1966, 21a, 1027-1041.
16. R. Serber, Phys. Rev., 1947, 72, 1114-1115.
17. H.W. Bertini, Phys. Rev. 1969, 188, 1711-1730.
18. K. Kwaitkowski, et al., Phys. Rev. Lett., 1983, 21, 1648-1651.
19. J.W. Wilson and S.L. Lamlin, Nucl. Sci. Eng., 1975, 57, 292 - 299.

CRITICAL CHARGE FOR SINGLE EVENT UPSETS

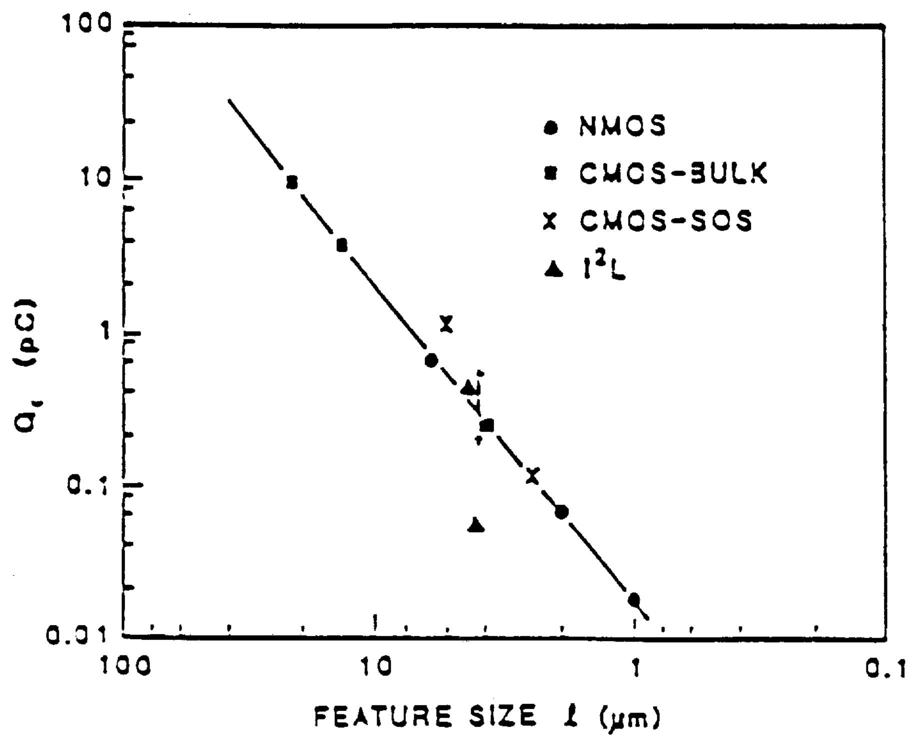

Figure 1
Critical charge Q_c as a function of feature size.

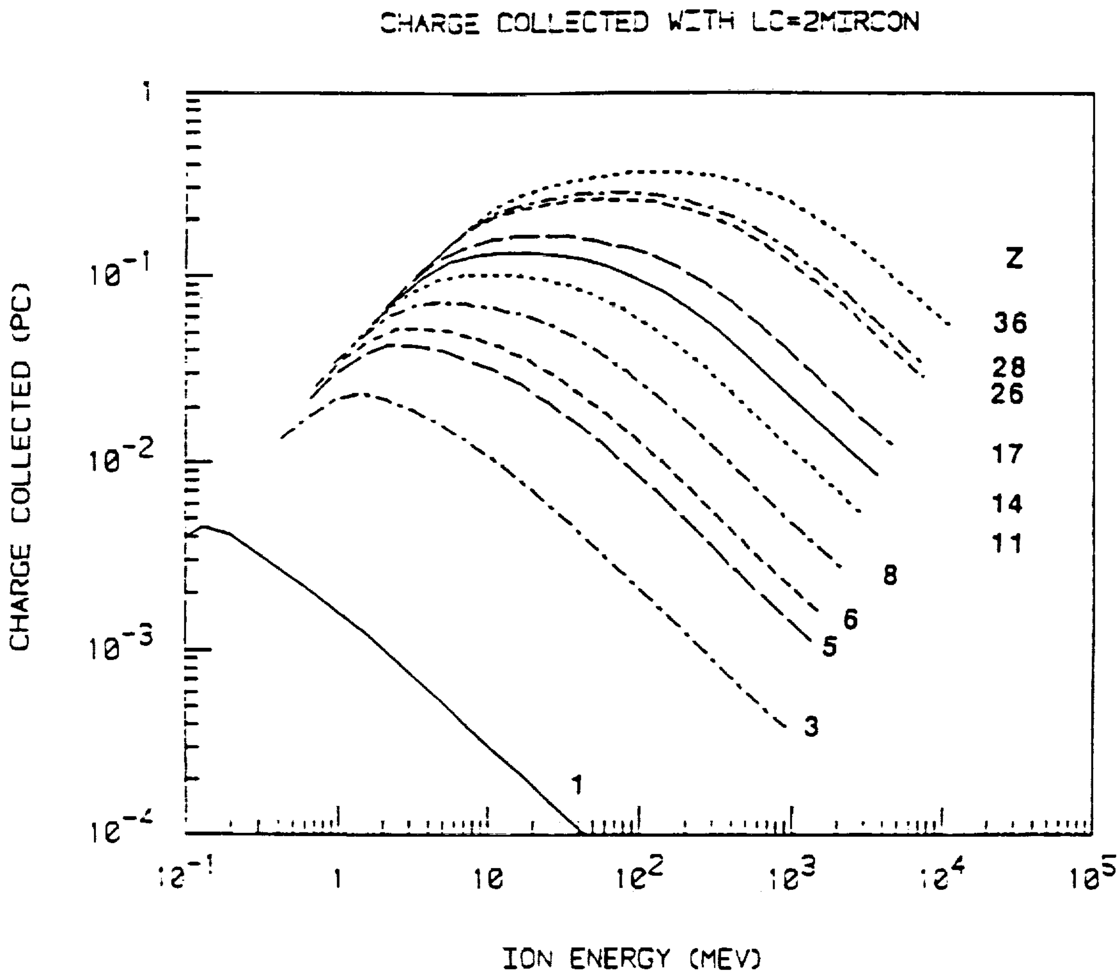

Figure 2
Charge collected as a function of ion energy.

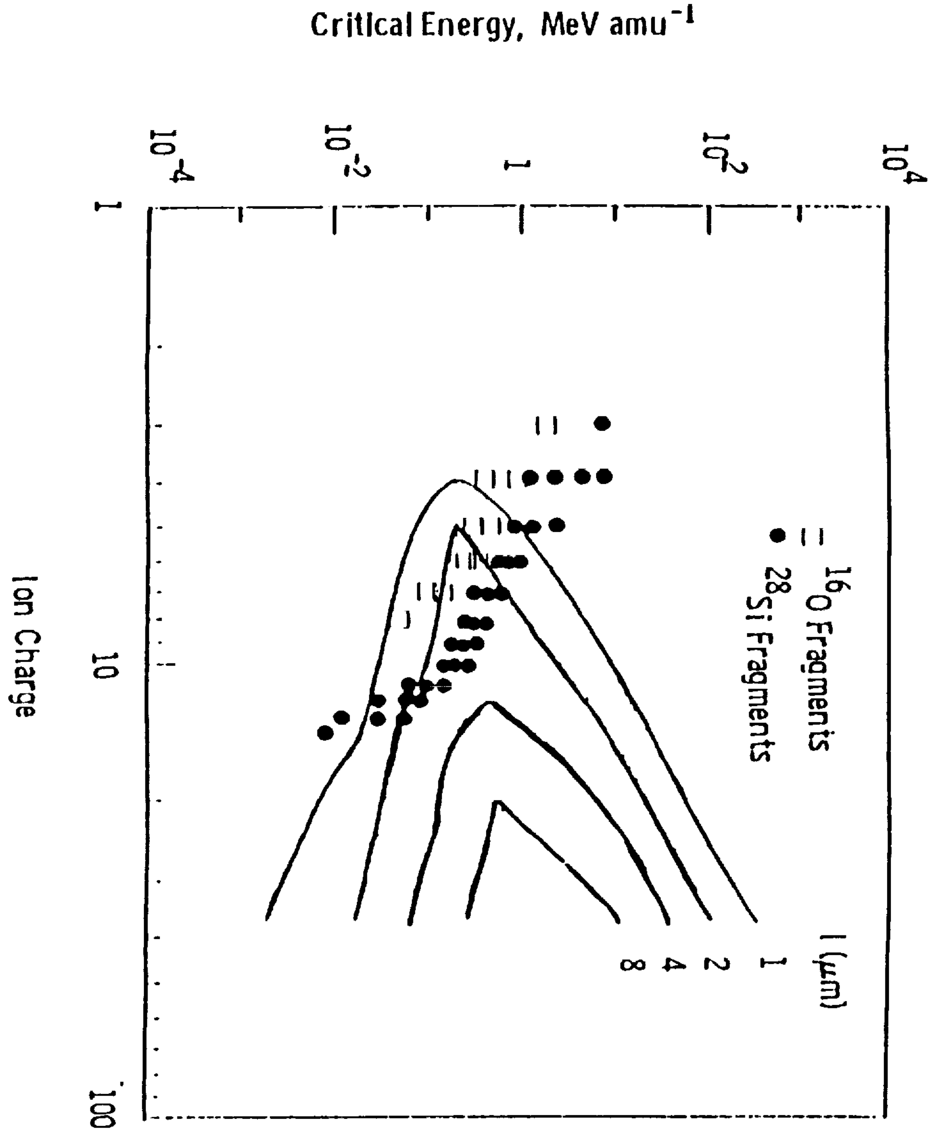

Figure 3

Critical energy as a function of ion charge for several feature sizes.

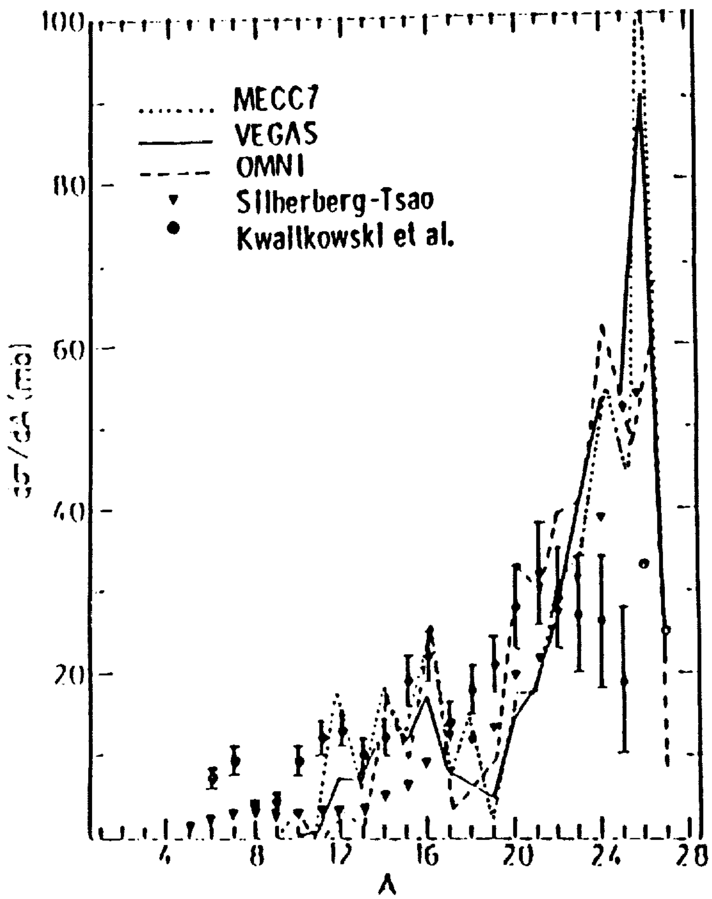

Figure 4

Fragmentation of ^{27}Al according to four models and the experiments of Kwaitkowski et al.

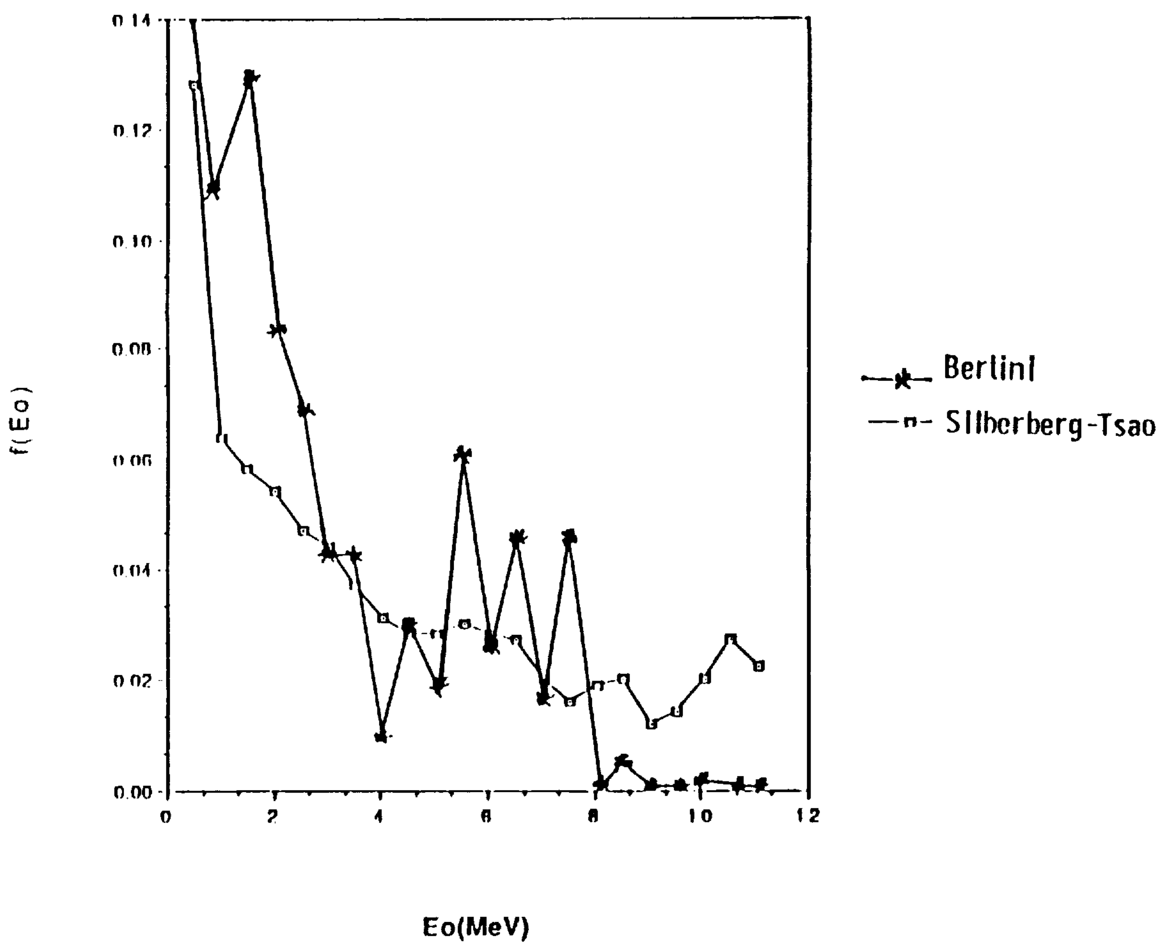

Figure 5

Spectrum of average recoil energy for the Bertini and the Silberberg-Tsao models.